E.Gedalin*, A.Moalem† and L.Razdolskaya‡

Department of Physics, Ben Gurion University, 84105, Beer Sheva, Israel

We show that for any effective field theory of colorless meson fields, the mixing schemes of particle states and decay constants are not only related but also determined exclusively by the kinetic and mass Lagrangian densities. In the general case, these are bilinear in terms of the intrinsic fields and involve non-diagonal kinetic and mass matrices. By applying three consecutive steps this Lagrangian can be reduced into the standard quadratic form in terms of the physical fields. These steps are : (i) the diagonalization of the kinetic matrix, (ii) rescaling of the fields, and (iii) the diagonalization of the mass matrix. In case, where the dimensions of the non-diagonal kinetic and mass sub-matrices are respectively, $k \times k$ and $n \times n$, this procedure leads to mixing schemes which involve $[k(k-1)/2] + [n(n-1)/2]$ angles and k field rescaling parameters. This observation holds true irrespective with the type of particle interactions presumed. The commonly used mixing schemes, correspond to a proper choice of the kinetic and mass matrices, and are derived as special cases. In particular, η-η' mixing, requires one angle, if and only if, the kinetic term with the intrinsic fields has a quadratic form.

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Mixing schemes of the pseudoscalar $\eta(547.3MeV) - \eta'(957MeV)$ mesons has attracted considerable interest in recent years [1]- [31]. The traditional approach based on the flavor $SU(3)$ quark model [32] involves a single mixing angle θ_P, an octet (F_8) and a singlet (F_0) radiative decay constants. The physical states η and η' are taken to be linear combinations of the octet η_8 and singlet η_0 states, i.e.,

$$\left(\begin{array}{c} \eta \\ \eta' \end{array} \right) = \Omega(\theta_P) \left(\begin{array}{c} \eta_8 \\ \eta_0 \end{array} \right) \ , \tag{0.1}$$

where $\Omega(\theta_P)$ stands for the unitary matrix,

$$\Omega(\theta_P) = \left(\begin{array}{cc} \cos\theta_P & -\sin\theta_P \\ \sin\theta_P & \cos\theta_P \end{array} \right) \ . \tag{0.2}$$

The corresponding physical decay constants F_η and $F_{\eta'}$ are presumably related to the octet and singlet decay constants through the same unitary transformation. The values of the mixing angle and decay constants are determined from phenomenological (model dependent) data analyses of various processes [1,2,7,9,11–13], but with a wide range of uncertainty. It is *ab initio* not clear why the state and decay constant mixing schemes should be identical or even similar. Indeed, several authors [3,4,10,14–16] suggested a two mixing angle scheme for the decay constants, e.g.,

$$\left(\begin{array}{cc} F^8_\eta & F^0_\eta \\ F^8_{\eta'} & F^0_{\eta'} \end{array} \right) = \bar\Theta(\theta_\eta, \theta_{\eta'}) \left(\begin{array}{cc} F_8 & 0 \\ 0 & F_0 \end{array} \right); \qquad \bar\Theta(\theta_\eta, \theta_{\eta'}) = \left(\begin{array}{cc} \cos\theta_\eta & -\sin\theta_{\eta'} \\ \sin\theta_\eta & \cos_{\eta'} \end{array} \right) \ , \tag{0.3}$$

while the particle states follow either the same transformation [20] or a single angle mixing pattern [10,14,16] as in Eqn.0.1. To explain data, the two mixing angles θ_η and $\theta_{\eta'}$ turned out to be considerably different [10,14,20]. Recently, Feldmann et al. [17,21,22] proposed that only in the quark flavor basis (QFB), $q\bar q = (u\bar u + d\bar d)/\sqrt{2}$ and $s\bar s$, the decay constants and particle states follow the same mixing pattern, namely,

$$\left(\begin{array}{cc} F^q_\eta & F^s_\eta \\ F^q_{\eta'} & F^s_{\eta'} \end{array} \right) = \Omega(\phi) \left(\begin{array}{cc} F_q & 0 \\ 0 & F_s \end{array} \right), \tag{0.4}$$

and,

*gedal@bgumail.bgu.ac.il

†moalem@bgumail.bgu.ac.il

‡ljuba@bgumail.bgu.ac.il

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \Omega(\phi) \begin{pmatrix} \eta_q \\ \eta_s \end{pmatrix} . \tag{0.5}$$

Clearly, the advantage of such a scheme is that only one mixing angle ϕ is required. It is to be stressed that by assumption this simplification is restricted to the case of two orthogonal QFB states only. Usually, in the octet-singlet basis, however, there is a need for one mixing angle $\theta_P = \phi - \theta_{ideal}$, $\theta_{ideal} = \arctan\sqrt{2}$ for the particle states and two mixing angles, Eqn. 0.3, for the decay constants. It is the purpose of the present note to show that for any effective field theory (EFT) irrespective with the field interactions presumed, the mixing schemes for the states and decay constants not only are related but also determined exclusively by the structure of the kinetic and mass Lagrangian densities.

We recall that the QCD Lagrangian exhibits a $SU(3)_L \otimes SU(3)_R$ symmetry which breaks down spontaneously to $SU(3)_V$, giving rise to an octet of light Goldstone pseudoscalar mesons. The axial $U(1)$ symmetry of the QCD Lagrangian is broken by the anomaly, giving rise to a ninth Goldstone pseudoscalar singlet meson. The corresponding octet and singlet state mix because of $SU(3)$ flavor symmetry breaking, reflecting a nontrivial nature of the QCD vacuum. Therefore, any EFT of colorless fields which allows for a consistent treatment of hadronic physics must also describe the mixing and mass spectrum of the physical mesons. For such theories, the most general form of the Goldstone meson kinetic and mass Lagrangian terms is,

$$L_{km} = \frac{1}{2}(\partial_\mu \Phi) K (\partial^\mu \Phi) + \frac{1}{2}\Phi M^2 \Phi , \tag{0.6}$$

where Φ stands for the intrinsic field matrix, K and M^2 are the kinetic and mass matrices. Usually, K and M^2 are non-diagonal and the Lagrangian L_{km} is bilinear rather than quadratic as invoked from the Klein-Gordon equation for the physical fields. In what follows we show that this expression can always be reduced into the standard quadratic form by applying three consecutive steps which transform the intrinsic fields into the physical fields, and in turn determine the mixing schemes for both the states and decay constants, uniquely.

As indicated already, the two matrices K and M^2 are, in general, non-diagonal. We first diagonalize K using the unitary transformation,

$$\Phi = \Upsilon \Phi' . \tag{0.7}$$

Following this step the Lagrangian becomes,

$$L_{km} = \frac{1}{2}(\partial_\mu \Phi') \hat{K} (\partial^\mu \Phi') + \frac{1}{2}\Phi' \Upsilon^{-1} M^2 \Upsilon \Phi' , \tag{0.8}$$

with $\hat{K} = diag(\kappa_1, \kappa_2, \ldots)$. The eigenvalues $\kappa_i (i = 1, 2, ...)$, however, are not necessarily equal 1, and we rescale the fields in order to restore the standard normalization of the kinetic term, i.e.,

$$\Phi' = R\Phi'' , \tag{0.9}$$

where $R = diag(1/\sqrt{\kappa_1}, 1/\sqrt{\kappa_2}, \ldots)$. With this second step, the kinetic term in terms of the renormalized fields Φ'' acquires the standard quadratic form and the mass matrix is,

$$\tilde{M}^2 = R\Upsilon^{-1} M^2 \Upsilon R . \tag{0.10}$$

As a last step we diagonalize the matrix $\tilde{M}^2$ via another unitary transformation of the fields Φ'' into the physical fields Φ_{ph},

$$\Phi'' = \Omega \Phi_{ph} . \tag{0.11}$$

With this last step the transformed mass matrix becomes $M^2_{ph} = diag(m_1^2, m_2^2, ...)$, where the eigenvalues $m_1, m_2, \ldots$ are to be identified with the physical meson masses. Altogether the three steps transform the intrinsic fields Φ into the physical fields Φ_{ph},

$$\Phi = \Theta \Phi_{ph} ; \quad \Theta = \Upsilon R \Omega . \tag{0.12}$$

We now turn to show that the meson decay constants F_{ph} transform in a similar way. We start from the usual definition of the decay constants,

$$< 0|J^i_{\mu 5}|\Phi^m_{ph} > \equiv iF^{im}_{ph} q_\mu , \tag{0.13}$$

where $J^i_{\mu 5}$ stands for the axial vector currents, and the indices i and m label the intrinsic and physical fields. From the Lagrangian Eqn. 0.6 and by substituting the transformation 0.12 we may write,

$$J_{\mu 5} = FK\partial_\mu \Phi = FK\Theta\partial_\mu \Phi_{ph} \ , \tag{0.14}$$

where $F = diag(F_1, F_2, \ldots)$ is the intrinsic decay constant matrix. Thus, the matrix of the physical decay constants is,

$$F_{ph} = FK\Theta = \tilde{F}\Theta \ , \tag{0.15}$$

where $\tilde{F} = FK$ is the matrix of renormalized intrinsic decay constants.

This complete our argument that the transformation Θ determines the mixing schemes for the particle states and the decay constants. Obviously the parameterization of this transformation depends on the dimensions of non-diagonal sub-matrices of K and M^2. Let the corresponding dimensions of these sub-matrices be $k \times k$ and $n \times n$, respectively. We may parameterize the orthogonal transformation Υ using $k(k-1)/2$ real independent mixing angles. Likewise, the Ω would be described by $n(n-1)/2$ independent mixing angles. We may then conclude that the mixing schemes involve at most, $[k(k-1)/2]+[n(n-1)/2]$ mixing angles and k rescaling parameters, the value of which are determined by the matrix elements of K and $\tilde{M}^2$. In the special case where the kinetic term is non diagonal, but gets diagonalized simultaneously with the mass matrix, the matrices commute (i.e. $k = n$) and the number of mixing angles reduces to $k(k-1)/2$ only. As an example, for the commonly considered case of two intrinsic states η_8 and η_0, where K is diagonal ($k = 1$) and M^2 is a 2×2 matrix, only one mixing angle is required. Should we include a third component, like a gluonium (η_g), K and M^2 are 3×3 matrices. The most commonly considered case is that corresponding to a diagonal kinetic and a non diagonal mass matrices. Then the transformation Θ involves *a priori* 3 mixing angles. With one of the mixing angles taken to be zero the gluonium component of one physical state vanishes. This leads to a two angle mixing scheme for the case of three particles. By taking a second angle to be zero, one decouples the gluonium from the $\eta_8 - \eta_0$ doublet, what yields again a one mixing angle pattern. Clearly, however, for the most general case of $\eta_8 - \eta_0$ mixing both K and M^2 are 2×2 non diagonal matrices, and therefore, the transformation Θ involves two mixing angles as well as two rescaling parameters.

Let us consider this last example in more details. The contributions of the η_0 and η_8 to the Lagrangian Eqn. 0.6 sum to,

$$L^{08}_{km} = \frac{1}{2}(\ \partial_\mu\eta_8 \ \ \partial_\mu\eta_0\ )K_{8,0}\begin{pmatrix} \partial^\mu\eta_8 \\ \partial^\mu\eta_0 \end{pmatrix} + \frac{1}{2}(\ \eta_8 \ \ \eta_0\ )\mathcal{M}^2(8,0)\begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix} \ , \tag{0.16}$$

with,

$$K_{8,0} = \begin{pmatrix} \kappa_{88} & \kappa_{08} \\ \kappa_{08} & \kappa_{00} \end{pmatrix} \ , \qquad \mathcal{M}^2(8,0) = \begin{pmatrix} m^2_{88} & m^2_{08} \\ m^2_{08} & m^2_{00} \end{pmatrix} \ . \tag{0.17}$$

Following the procedure outlined above we first diagonalize the matrix $K_{8,0}$ using the unitary transformation,

$$\begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix} = \Upsilon \begin{pmatrix} \bar{\eta}_8 \\ \bar{\eta}_0 \end{pmatrix} \ , \qquad \Upsilon = \begin{pmatrix} \cos\lambda & \sin\lambda \\ -\sin\lambda & \cos\lambda \end{pmatrix} \ , \tag{0.18}$$

which leads to,

$$L^{08}_{km} = \frac{1}{2}\kappa_8(\partial_\mu\bar{\eta}_8)^2 + \frac{1}{2}\kappa_0(\partial_\mu\bar{\eta}_0)^2 + \frac{1}{2}(\bar{\eta}_8, \bar{\eta}_0)\Upsilon^{-1}\mathcal{M}^2\Upsilon\begin{pmatrix} \bar{\eta}_8 \\ \bar{\eta}_0 \end{pmatrix} \ . \tag{0.19}$$

Here κ_0, and κ_8 are eigenvalues of the matrix $K_{8,0}$. Next we rescale the pseudoscalar fields according to,

$$\begin{pmatrix} \bar{\eta}_8 \\ \bar{\eta}_0 \end{pmatrix} = R\begin{pmatrix} \hat{\eta}_8 \\ \hat{\eta}_0 \end{pmatrix} \ , \qquad R = diag(z,\ f) \equiv diag(1/\sqrt{\kappa_8}, 1/\sqrt{\kappa_0}) \ . \tag{0.20}$$

Following these two transformations, the kinetic term acquires the standard quadratic form, $(1/2)[(\partial_\mu\hat{\eta}_8)^2 + (\partial_\mu\hat{\eta}_0)^2]$ and the mass matrix becomes,

$$\hat{\mathcal{M}}^2(8,0) = R\Upsilon^{-1}\mathcal{M}^2(8.0)\Upsilon R = \begin{pmatrix} \hat{m}^2_{88} & \hat{m}^2_{80} \\ \hat{m}^2_{80} & \hat{m}^2_{00} \end{pmatrix} . \tag{0.21}$$

We may now diagonalize this matrix by another unitary transformation,

$$\begin{pmatrix} \hat{\eta}_8 \\ \hat{\eta}_0 \end{pmatrix} = \Omega \begin{pmatrix} \eta \\ \eta' \end{pmatrix} , \qquad \Omega = \begin{pmatrix} \cos\chi & \sin\chi \\ -\sin\chi & \cos\chi \end{pmatrix} . \tag{0.22}$$

The relations between the η_8 and η_0 and physical fields $\eta,\ \eta'$ is then given by,

$$\begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix} = \Theta \begin{pmatrix} \eta \\ \eta' \end{pmatrix} , \tag{0.23}$$

where,

$$\Theta = \Upsilon R \Omega = \begin{pmatrix} z\cos\lambda\cos\chi - f\sin\lambda\sin\chi & z\cos\lambda\sin\chi + f\sin\lambda\cos\chi \\ -z\sin\lambda\cos\chi - f\cos\lambda\sin\chi & -z\sin\lambda\sin\chi + f\cos\lambda\cos\chi \end{pmatrix} . \tag{0.24}$$

Note that the transformation Θ depends on two mixing angles λ and χ and two rescaling parameters z and f. To write Θ in a more convenient and familiar form, we define new parameters,

$$z_1^2 = z^2\cos^2\chi + f^2\sin^2\chi, \quad z\cos\chi = z_1\cos\psi_1, \quad f\sin\chi = -z_1\sin\psi_1, \tag{0.25}$$

$$z_2^2 = f^2\cos^2\chi + z^2\sin^2\chi, \quad f\cos\chi = z_2\cos\psi_2, \quad z\sin\chi = -z_2\sin\psi_2, \tag{0.26}$$

$$\tan\psi_1 = -\frac{f}{z}\tan\chi, \qquad \tan\psi_1 = \frac{f^2}{z^2}\tan\psi_2, \tag{0.27}$$

$$\theta_\eta = \lambda - \psi_2 , \qquad \theta_{\eta'} = \lambda - \psi_1 . \tag{0.28}$$

and write Θ in the form 0.3 [14,20]

$$\Theta = \begin{pmatrix} \cos\theta_{\eta'} & \sin\theta_\eta \\ -\sin\theta_{\eta'} & \cos\theta_\eta \end{pmatrix} \bar{Z} , \tag{0.29}$$

with $\bar{Z} = diag(z_1, z_2)$. This exact general form of the field transformation includes two mixing angles θ_η and $\theta_{\eta'}$, as well as two rescaling parameters z_1 and z_2. A similar two mixing angle scheme was proposed by Escribano and Frère [20]. In our scheme, however, the physical η and η' are orthogonal.

We now turn to demonstrate that the pseudoscalar decay constants F_P^i $(i = 8, 0;\ P = \eta,\ \eta')$ are related to the octet and singlet decay constants $F_8,$ and F_0, the same way the physical $\eta,\ \eta'$ are related to the intrinsic $\eta_8,\ \eta_0$ states. The axial vector currents read,

$$\begin{pmatrix} J^8_\mu \\ J^0_\mu \end{pmatrix} = FK \begin{pmatrix} \partial_\mu\eta_8 \\ \partial_\mu\eta_0 \end{pmatrix} , \tag{0.30}$$

where $F = diag(F_8,\ F_0)$. The matrix of the corresponding physical decay constants F^i_{ph} is,

$$\begin{pmatrix} F^8_\eta & F^8_{\eta'} \\ F^0_\eta & F^0_{\eta'} \end{pmatrix} = FK\Theta = F\tilde{\Theta} . \tag{0.31}$$

Since,

$$K\Upsilon R = \Upsilon R^{-1} , \tag{0.32}$$

one obtains,

$$\tilde{\Theta} = \Upsilon R^{-1}\Omega = \sqrt{\kappa_8\kappa_0} \begin{pmatrix} f\cos\lambda\cos\chi - z\sin\lambda\sin\chi & f\cos\lambda\sin\chi + z\sin\lambda\cos\chi \\ -f\sin\lambda\cos\chi - z\cos\lambda\sin\chi & -f\sin\lambda\sin\chi + z\cos\lambda\cos\chi \end{pmatrix} . \tag{0.33}$$

Again we introduce new parameters,

$$\tilde{z}_1^2 = f^2\cos^2\chi + z^2\sin^2\chi, \quad f\cos\chi = \tilde{z}_1\cos\tilde{\psi}_1, \quad z\sin\chi = -\tilde{z}_1\sin\tilde{\psi}_1, \tag{0.34}$$

$$\tilde{z}_2^2 = z^2\cos^2\chi + f^2\sin^2\chi, \quad z\cos\chi = \tilde{z}_2\cos\tilde{\psi}_2, \quad f\sin\chi = -\tilde{z}_2\sin\tilde{\psi}_2, \tag{0.35}$$

$$\tan\tilde{\psi}_1 = -\frac{z}{f}\tan\chi, \qquad \tan\tilde{\psi}_2 = \frac{f^2}{z^2}\tan\tilde{\psi}_1. \tag{0.36}$$

From Eqns. 0.36 and 0.27 $\tilde{\psi}_1 = \psi_2$ and $\tilde{\psi}_2 = \psi_1$ and after simple algebraic manipulations one obtains,

$$\tilde{\Theta} = \Lambda \Xi, \qquad \Lambda = \begin{pmatrix} \cos\theta_\eta & \sin\theta_{\eta'} \\ -\sin\theta_\eta & \cos\theta_{\eta'} \end{pmatrix} , \tag{0.37}$$

with $\Xi = diag(\xi_1, \xi_2) = diag(\tilde{z}_1\sqrt{\kappa_8\kappa_0},\ \tilde{z}_2\sqrt{\kappa_8\kappa_0})$. Hence the pseudoscalar decay constants mix according to,

$$\begin{pmatrix} F_\eta^8 & F_{\eta'}^8 \\ F_\eta^0 & F_{\eta'}^0 \end{pmatrix} = F\Lambda\Xi , \tag{0.38}$$

This relation should be compared with the corresponding relation for the fields (see Eqns.0.23,0.29),

$$(\ \eta \ \ \eta'\ ) = (\ \tilde{\eta}_8 \ \ \tilde{\eta}_0\ )\Lambda \bar{Z}^{-1} , \tag{0.39}$$

where,

$$(\ \tilde{\eta}_8 \ \ \tilde{\eta}_0\ ) = (\ \eta_8/\Delta \ \ \eta_0/\Delta\ ) , \tag{0.40}$$

and $\Delta = \cos(\theta_{\eta'} - \theta_\eta)$. We may thus conclude that the *renormalized* decay constants and fields follow the same transformation Λ. Clearly, even in the limit of exact nonet symmetry, where $F_8 = F_0$, the reduction of the meson kinetic term to the standard quadratic form may lead to renormalized decay constants $\tilde{F}_8 \neq \tilde{F}_0$.

It must be stressed again that, for any EFT for which the kinetic term has a bi-linear form, the mixing schemes for the states and decay constants involve two angles and two rescaling parameters. Clearly, for a diagonal kinetic matrix, $\lambda = 0$, ψ_1 and ψ_2 vanish, and the results reduce to a one angle mixing scheme (Eqn.0.1). The scheme of Feldmann et al. [17,21,22] corresponds to ideal mixing where flavorless mesons are represented by fields with or without strange quark content. Their assumption that, the states and decay constants follow the same one angle mixing scheme (Eqns.0.4-0.5) is equivalent to the assumption that the kinetic term has the standard form. This immediately leads to one mixing angle scheme with neither field nor decay constant renormalizations.

In summary for any EFT the particle and decay constant mixing is defined solely by the effective kinetic and mass terms of the particle Lagrangian. Since radiative corrections may only alter the values of the matrix elements of K and M^2 but do not change the general form of L_{km} this statement is valid for any type of interactions the theory accounting for. Previously suggested mixing schemes correspond to a proper choice of the kinetic matrix. Particularly, $\eta - \eta'$ mixing require one mixing angle scheme, if and only if, the kinetic term for the intrinsic fields has a quadratic form. Such are the traditional scheme [32] and the one proposed by Feldmann et al. [17,21,22]. A bi-linear (i.e. with non diagonal matrix) kinetic term leads to a two mixing angle scheme similar but not identical to the one proposed by Escribano and Frère [20].

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